THE NCEP CLIMATE FORECAST SYSTEM

THE ENVIRONMENTAL MODELING CENTER

NCEP/NWS/NOAA

Four essential components:

1. Development and testing of an upgraded data assimilation and forecast model for the new system.
2. Making a new Reanalysis of the atmosphere, ocean, seaice and land over the 32-year period (1979-2010), which is required to provide consistent initial conditions for:
3. Making a complete Reforecast of the new CFS over the 29-year period (1982-2010), in order to provide stable calibration and skill estimates of the new system, for operational subseasonal and seasonal prediction at NCEP
4. Operational Implementation of the new system

An upgrade to the NCEP Climate Forecast System (CFS) was implemented on March 30, 2011.

This upgrade involved changes to all components of the CFS, namely:

- **improvements to the data assimilation of the atmosphere with the new NCEP Gridded Statistical Interpolation Scheme (GSI) and major improvements to the physics and dynamics of operational NCEP Global Forecast System (GFS)**

- **improvements to the data assimilation of the ocean and ice with the NCEP Global Ocean Data Assimilation System, (GODAS) and a new GFDL MOM4 Ocean Model**

- **improvements to the data assimilation of the land with the NCEP Global Land Data Assimilation System, (GLDAS) and a new NCEP Noah Land model**

For a new CFS implementation (contd)

1. An atmosphere at high horizontal resolution (spectral T382, ~38 km) and high vertical resolution (64 sigma-pressure hybrid levels)

2. An interactive ocean with 40 levels in the vertical, to a depth of 4737 m, and horizontal resolution of 0.25 degree at the tropics, tapering to a global resolution of 0.5 degree northwards and southwards of 10N and 10S respectively

3. An interactive 3 layer sea-ice model

4. An interactive land model with 4 soil levels

There are three main differences with the earlier two NCEP Global Reanalysis efforts:

- Much higher horizontal and vertical resolution (T382L64) of the atmosphere (earlier efforts were made with T62L28 resolution)

- The guess forecast was generated from a coupled atmosphere – ocean – seaice - land system

- Radiance measurements from the historical satellites were assimilated in this Reanalysis

To conduct a Reanalysis with the atmosphere, ocean, seaice and land coupled to each other was a novelty, and will hopefully address important issues, such as the correlations between sea surface temperatures and precipitation in the global tropics, etc.

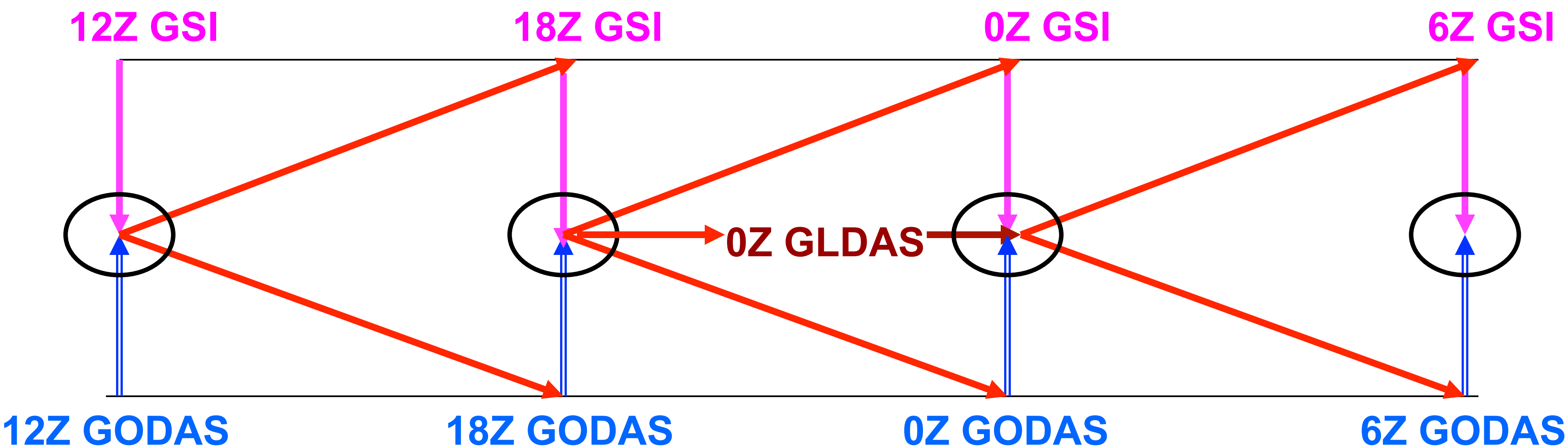
Changes to Data Assimilation Systems

R2 TO CDASv2

GODASv1 to GODASv2

GLDAS

ONE DAY OF CDAS



9-hr coupled T574L64 forecast guess (GFS + MOM4 + Noah)

	R2 (1997)	CDASv2 (2011)
Vertical coordinate	Sigma	Sigma/pressure
Spectral resolution	T62	T574
Horizontal resolution	~210 ***km***	~27 ***km***
Vertical layers	28	64
Top level pressure	~3 ***hPa***	0.266 ***hPa***
Layers above 100 hPa	~7	~24
Layers below 850 hPa	~6	~13
Lowest layer thickness	~40 ***m***	~20 ***m***
Analysis scheme	SSI	GSI
Satellite data	NESDIS temperature retrievals (2 satellites)	Radiances (all satellites)

Bob Kistler, EMC

GODAS – 3DVAR

- **Version**
  - Changing from a version based on MOM V3 to one based on MOM4p0d
  - As was the case with MOM4p0d, the code has been completely rewritten from Fortran 77 to Fortran 90.
- **Domain and Resolution**
  - Changing to a global domain.
  - Increasing resolution to match the MOM4p0d configuration used in the CFS: $1/2^o$x$1/2^o$ ($1/4^o$ within 10^o of the equator); 40 Z-levels.
- **Functionality**
  - Adding the ability to compile the 3DVAR analysis in either an executable combining the analysis with MOM or an executable containing only the analysis. The latter formulation is used with the CFS where it reads the forecast from a restart file produced by the coupled CFS, does the analysis, and updates the restart file.
  - Adding relaxation of surface temperature and salinity to observed fields under the control of the 3DVAR analysis.
- **Data**
  - The data sets that can be assimilated remain unchanged from the current operational GODAS: XBTs, tropical moorings (TAO, TRITON, PIRATA, RAMA), Argo floats, CTDs), altimetry (JASON-x).

Dave Behringer, EMC

SST Analysis

CFSv1:Weekly OI.v2	*CFSv2:Daily OI from NCDC*
• Grid: 1°	• Grid: 0.25°
• Data: 7 days of satellite, ship & buoy. Plus, SSTs simulated from 7-day median ice.	• Data: **3 days** satellite, ship & buoy. Plus, SSTs simulated from 7-day median ice

• Satellite data
  • **Infrared AVHRR**
  – 7-Day large-scale satellite bias correction (Poisson)
	• Satellite data
	  • **Infrared AVHRR**
	  • **Microwave AMSR**
	  – 7-Day large-scale satellite bias correction (EOT's)

• Spatial error correlation: ~ 700 km	• Spatial error correlation: ~ 100 km

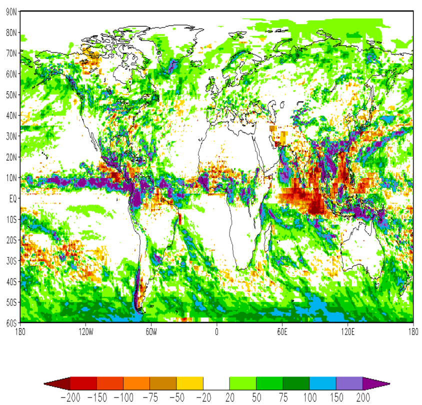
Diane Stokes and Dick Reynolds

Global Land Data Assimilation System (GLDAS)

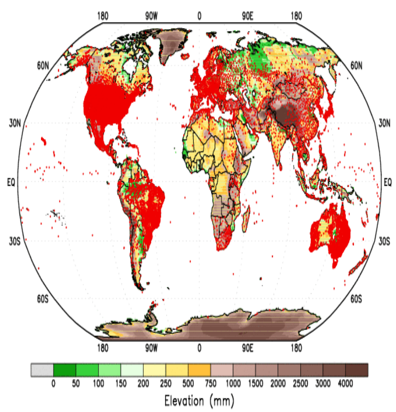
- **GLDAS** (running Noah LSM under NASA/Land Information System) forced with CFSv2/*GDAS* atmospheric data assimilation output and blended precipitation in a semi-coupled mode, versus no GLDAS in CFSv1, where CFSv2/**GLDAS** ingested into CFSv2/*GDAS* once every 24-hours.

- In CFSv2/**GLDAS**, blended precipitation a function of satellite (CMAP; heaviest weight in tropics), surface gauge (heaviest in middle latitudes) and *GDAS* (modeled; high latitude), vs use of model precipitation comparison with CMAP product and corresponding adjustment to soil moisture in CFSv1.

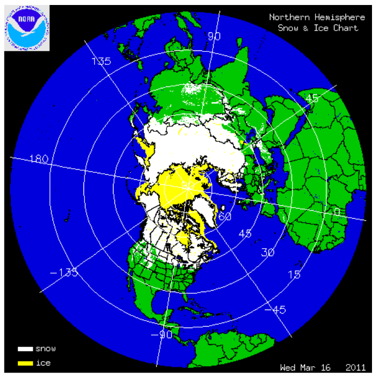
- Snow cycled in CFSv2/**GLDAS** if model within 0.5x to 2.0x of the observed value (IMS snow cover, and AFWA snow depth products), else adjusted to 0.5 or 2.0 of observed value.



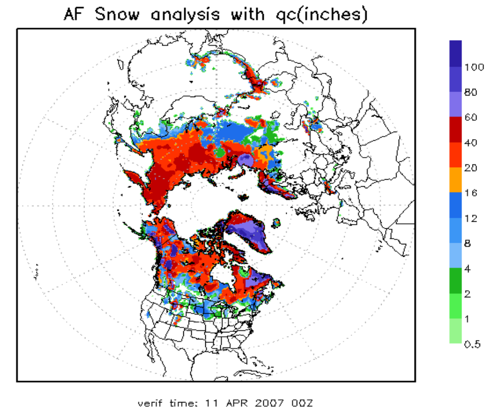
GDAS-CMAP precip



Gauge locations



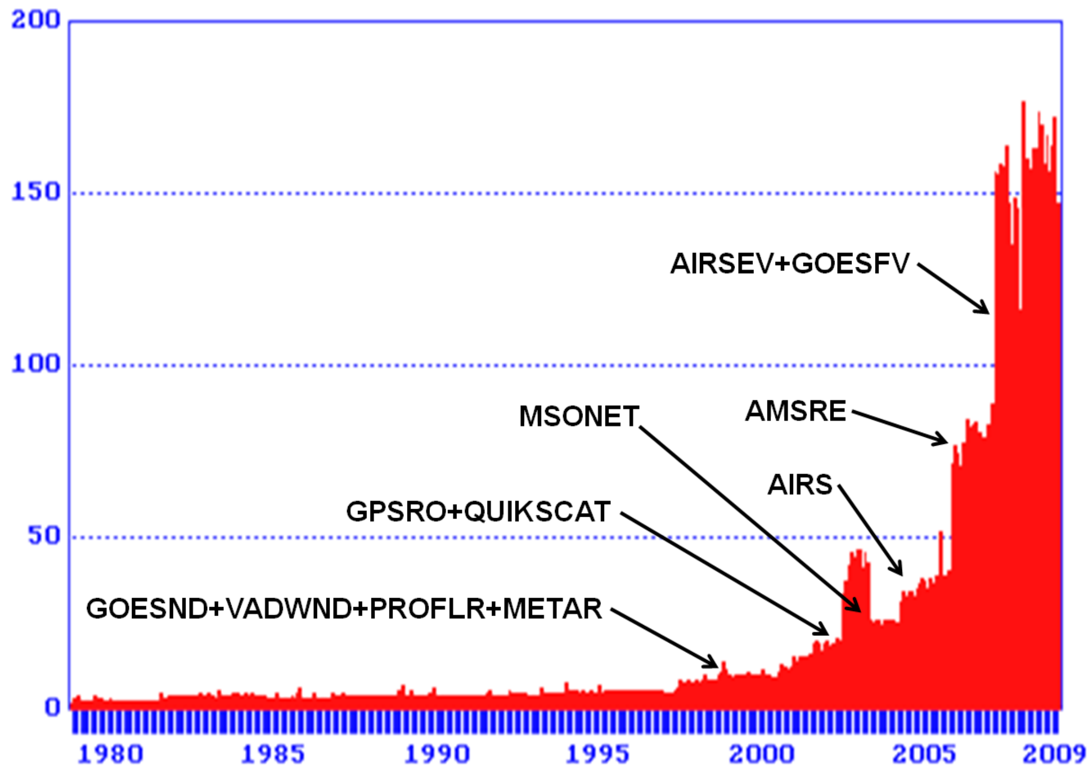
IMS snow cover



AFWA snow depth

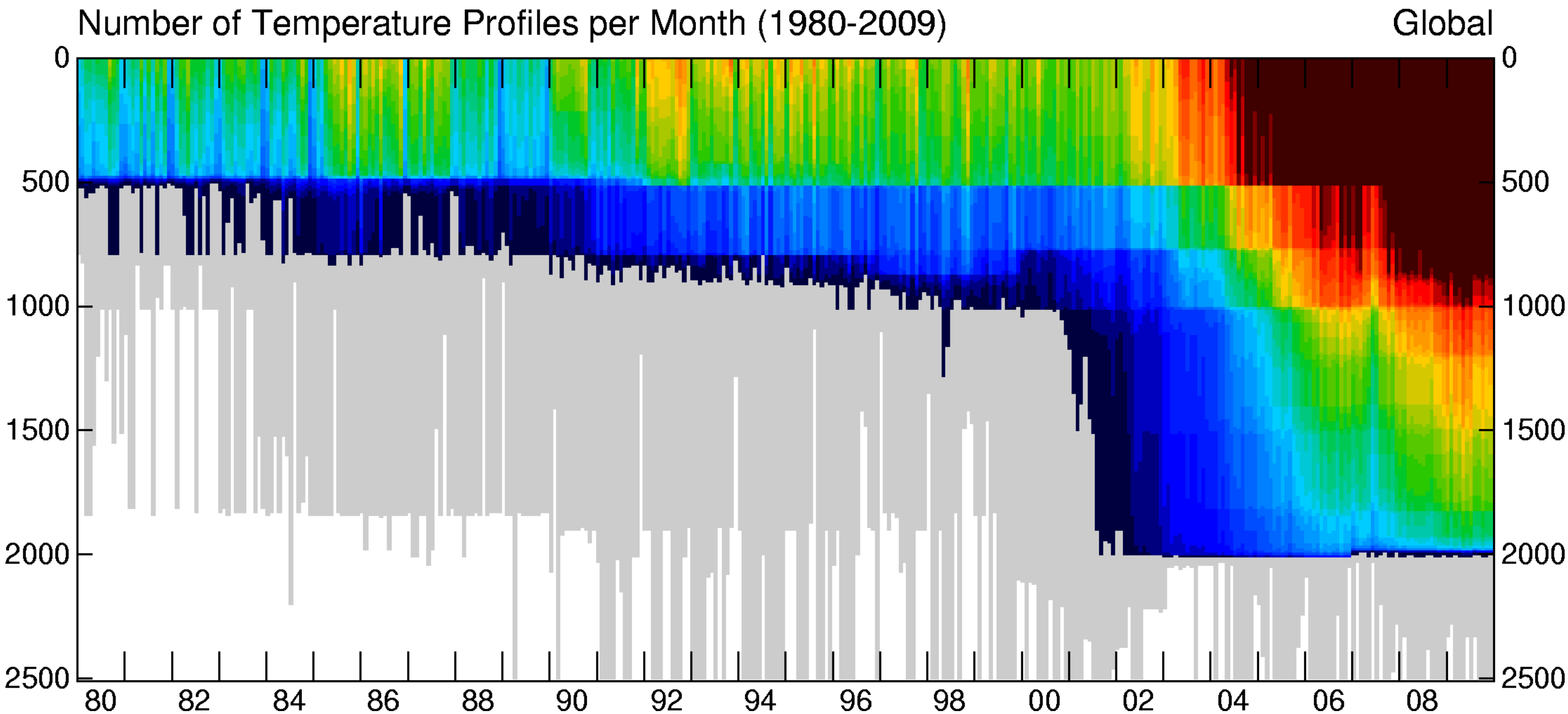
Mike Ek, EMC

CFSR data dump volumes, 1978-2009, in GB/month



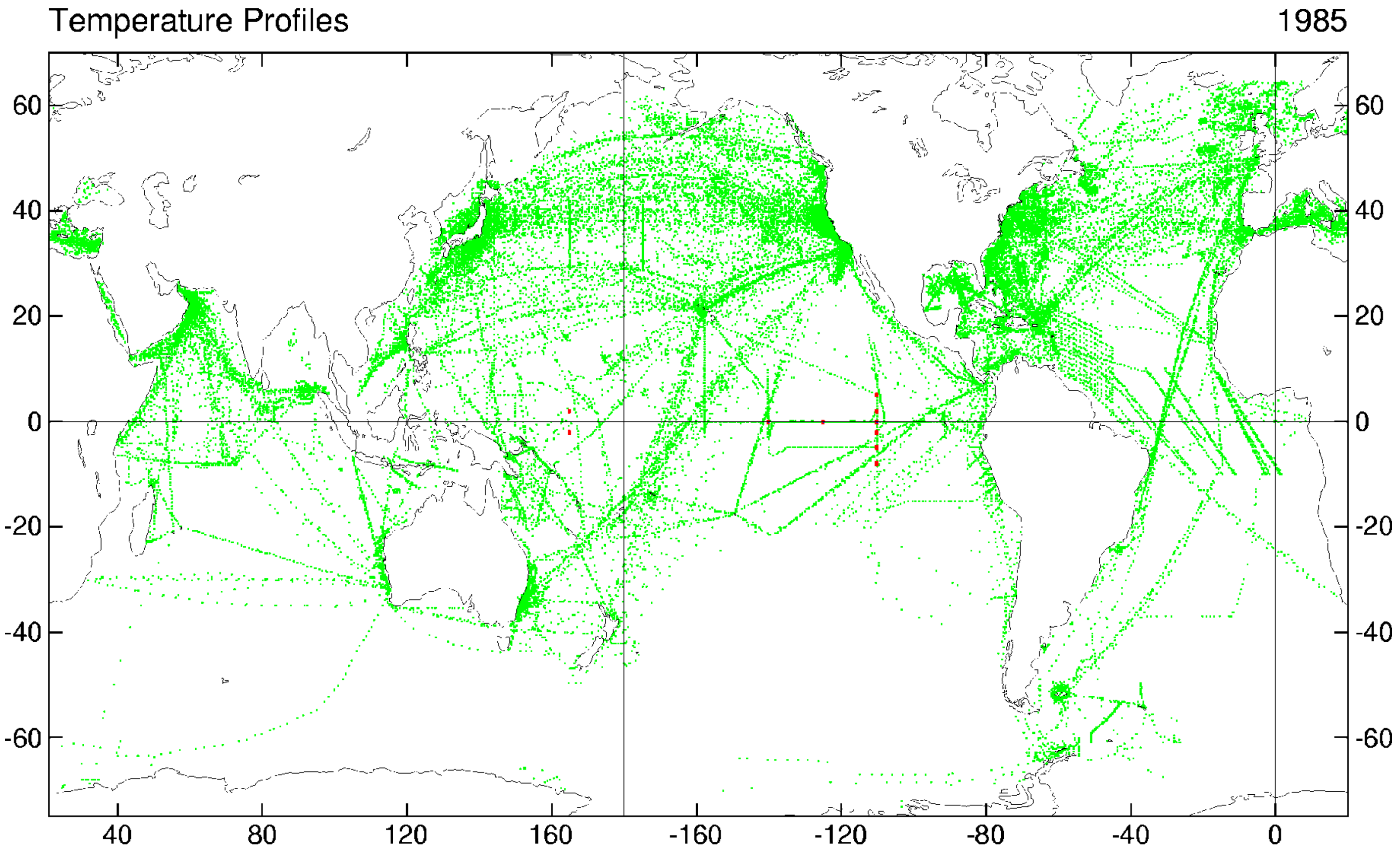
Courtesy: Jack Woollen

The global number of temperature observations assimilated per month by the ocean component of the CFSR as a function of depth for the years 1980-2009.



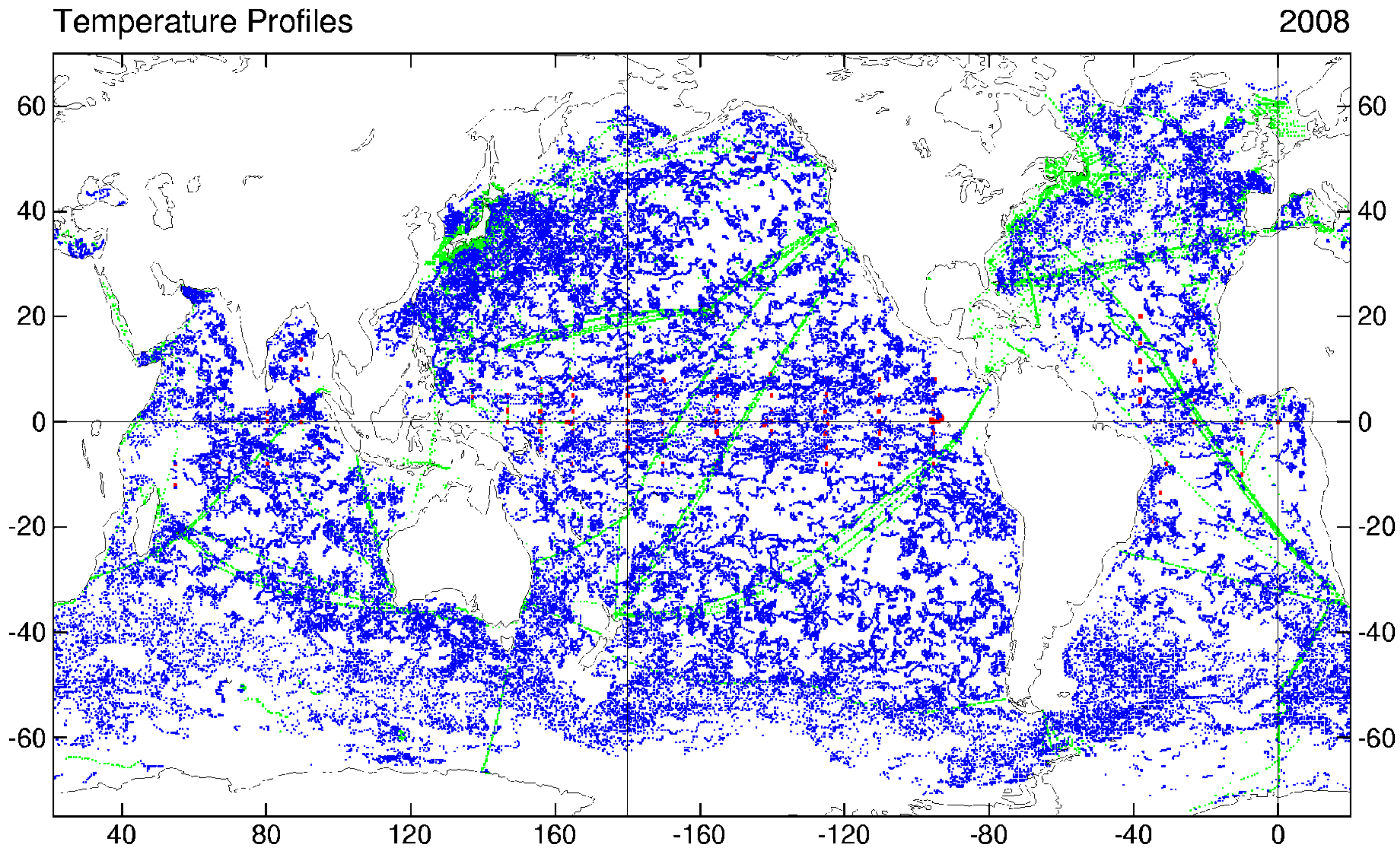
Courtesy: Dave Behringer

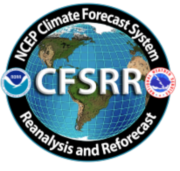
The global distribution of all temperature profiles assimilated by the ocean component of the CFSR for the year 1985. The distribution is dominated by XBT profiles collected along shipping routes.



Courtesy: Dave Behringer

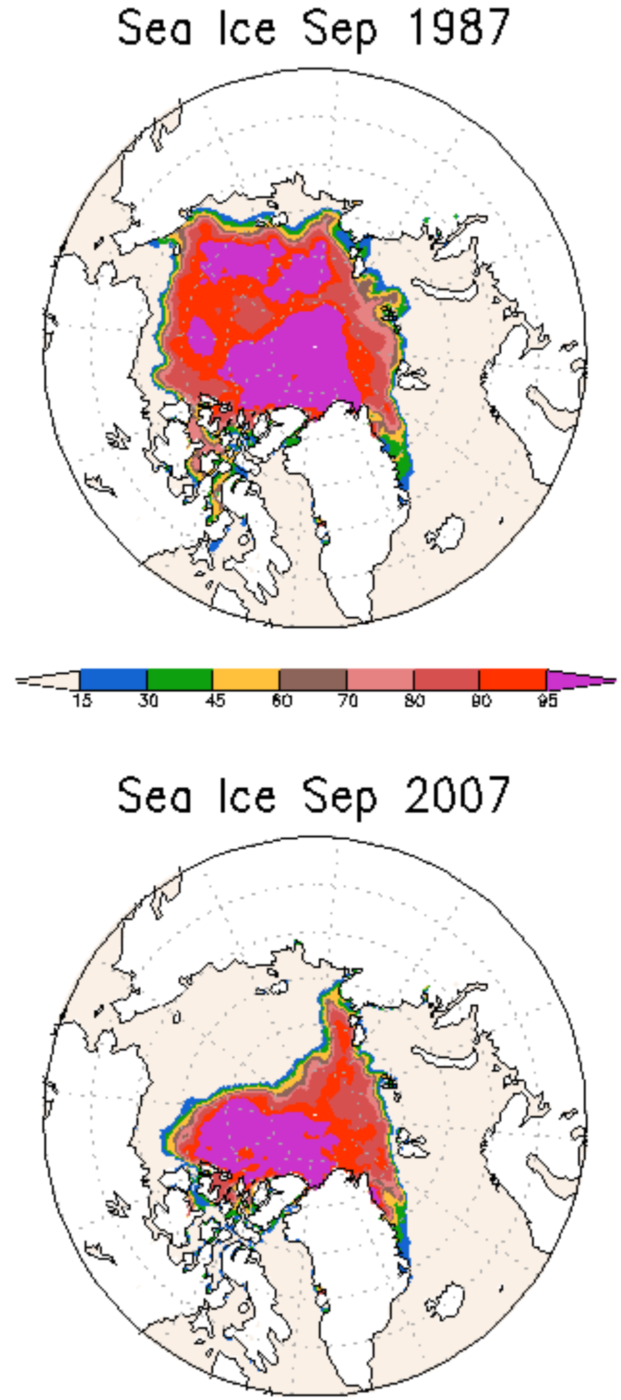
The global distribution of all temperature profiles assimilated by the ocean component of the CFSR for the year 2008. The Argo array (blue) provides a nearly uniform global distribution of temperature profiles





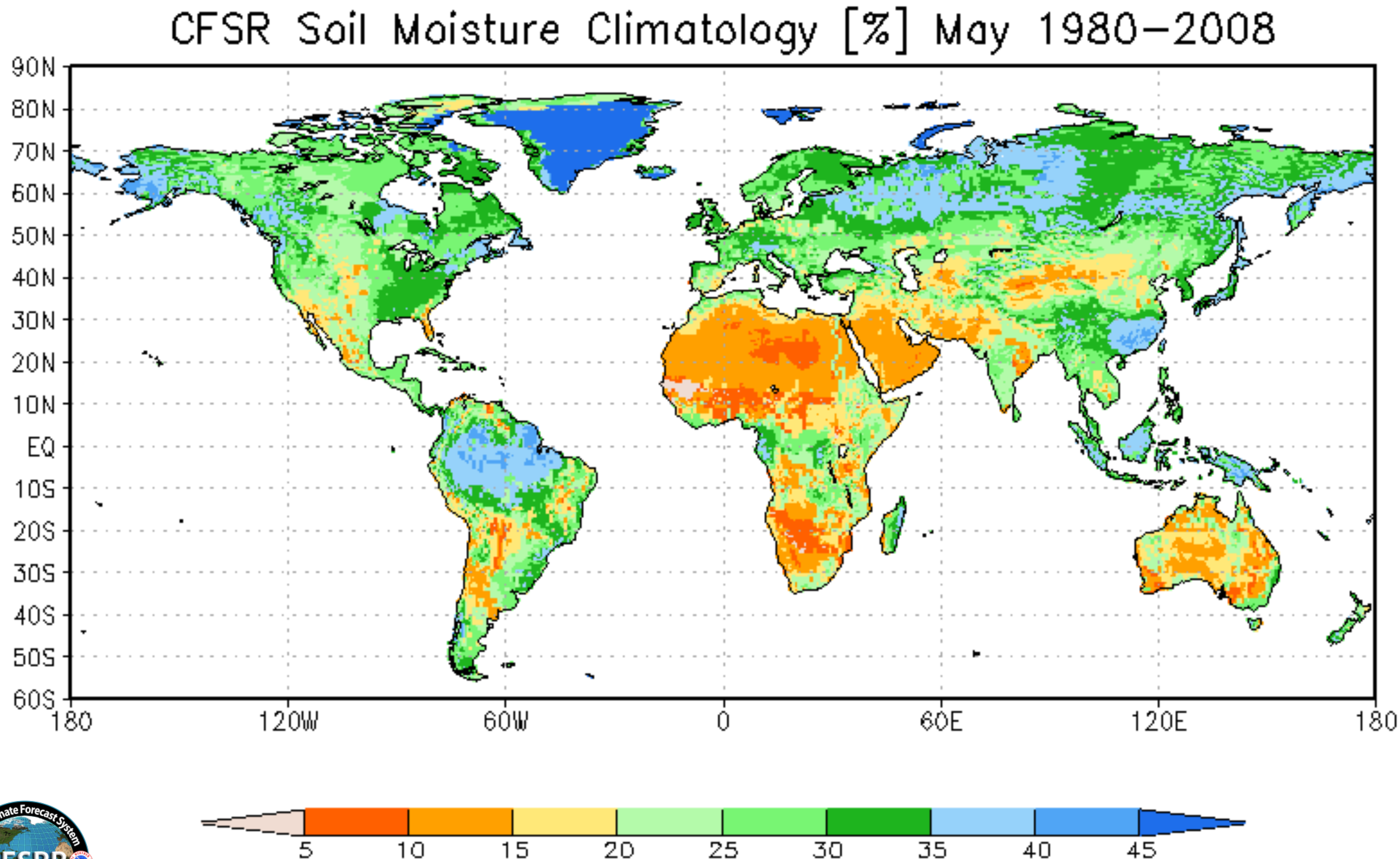
Courtesy: Dave Behringer

Monthly mean sea ice concentration for the Arctic from CFSR (6-hr forecasts)



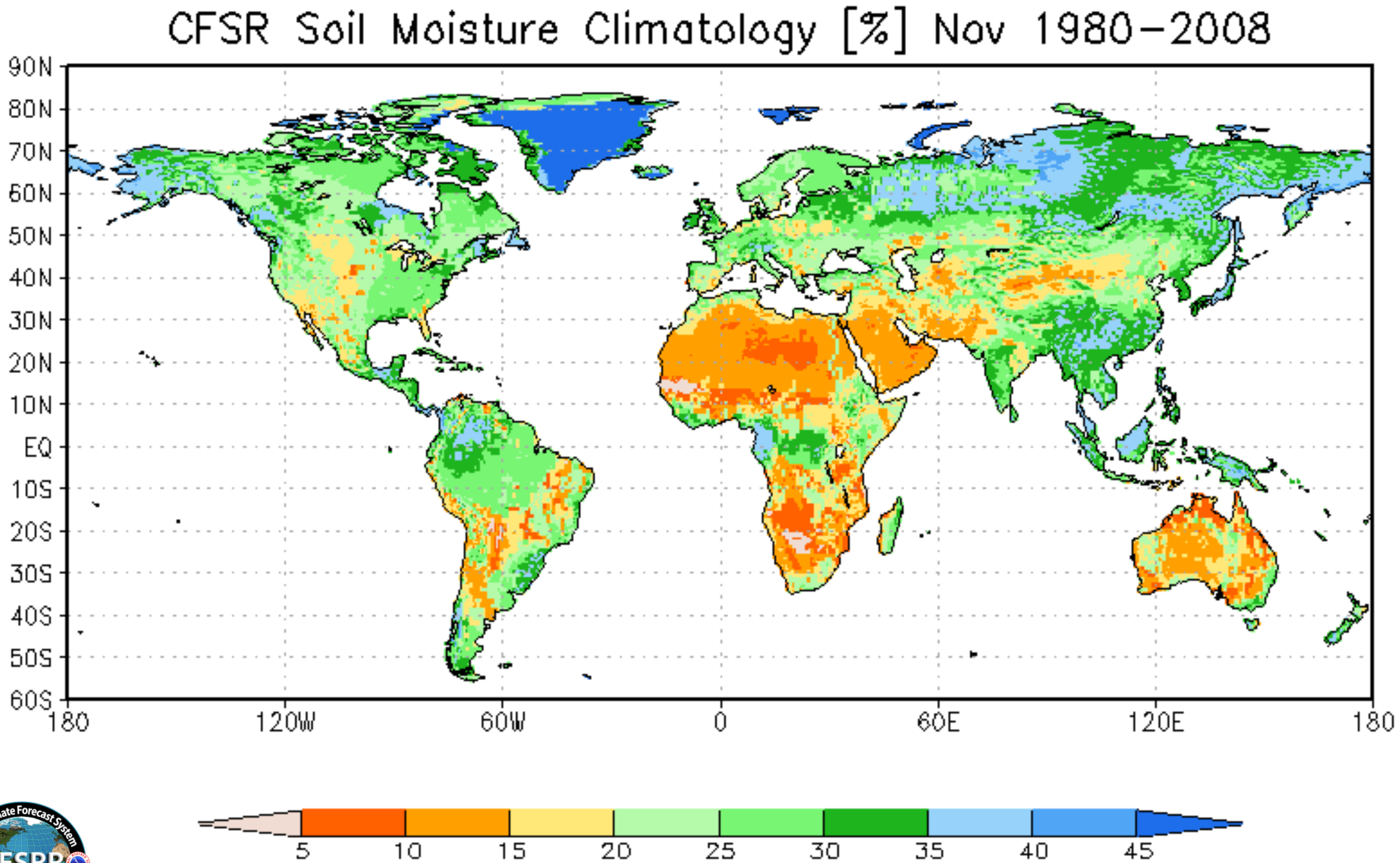
Courtesy: Xingren Wu

2-meter volumetric soil moisture climatology of CFSR for May averaged over 1980-2008.



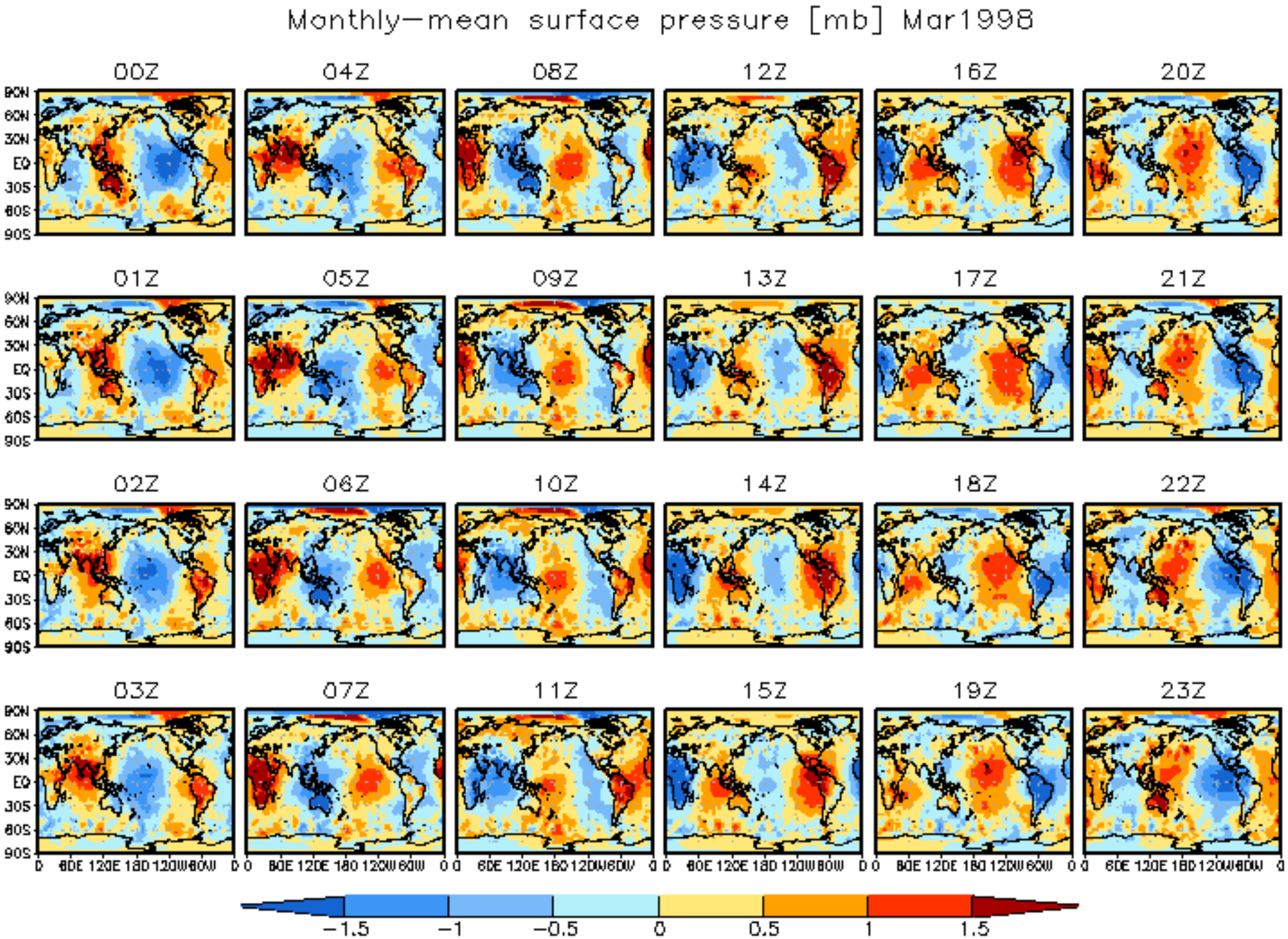
Courtesy: Jesse Meng

2-meter volumetric soil moisture climatology of CFSR for Nov averaged over 1980-2008.



Courtesy: Jesse Meng

Monthly mean hourly surface pressure with the daily mean subtracted for the month of March 1998

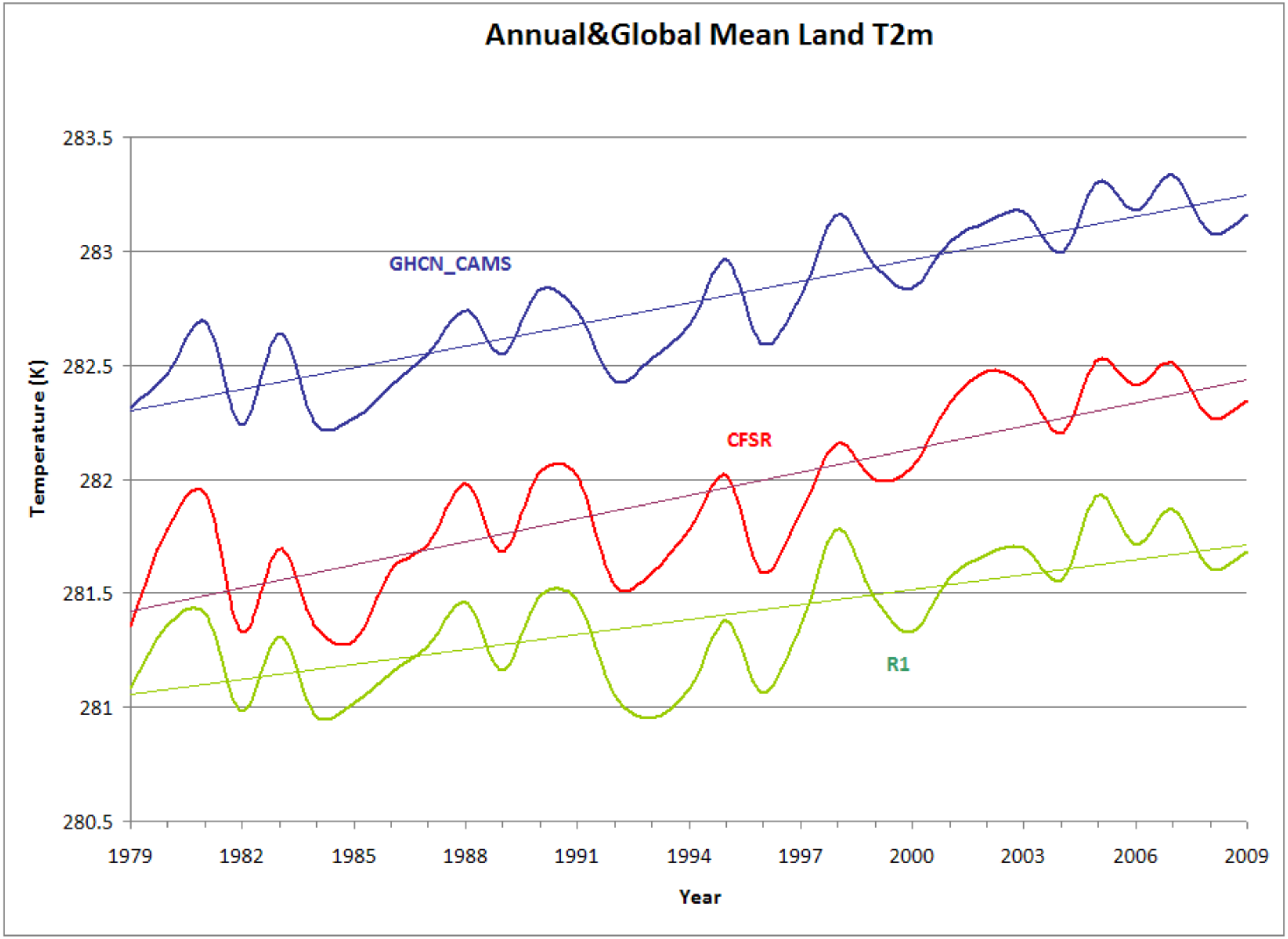


Courtesy: Huug van den Dool

Another innovative feature of the CFSR GSI is the use of the historical concentrations of carbon dioxide when the historical TOVS instruments were retrofit into the CRTM.

Satellite Platform	Mission Mean (ppmv)b
TIROS-N	337.10
NOAA-6	340.02
NOAA-7	342.96
NOAA-8	343.67
NOAA-9	355.01
NOAA-10	351.99
NOAA-11	363.03
NOAA-12	365.15
GEOS-8	367.54
GEOS-0	362.90
GEOS-10	370.27
NOAA-14 to NOAA-18	380.00
IASI METOP-A	389.00
NOAA-19	391.00

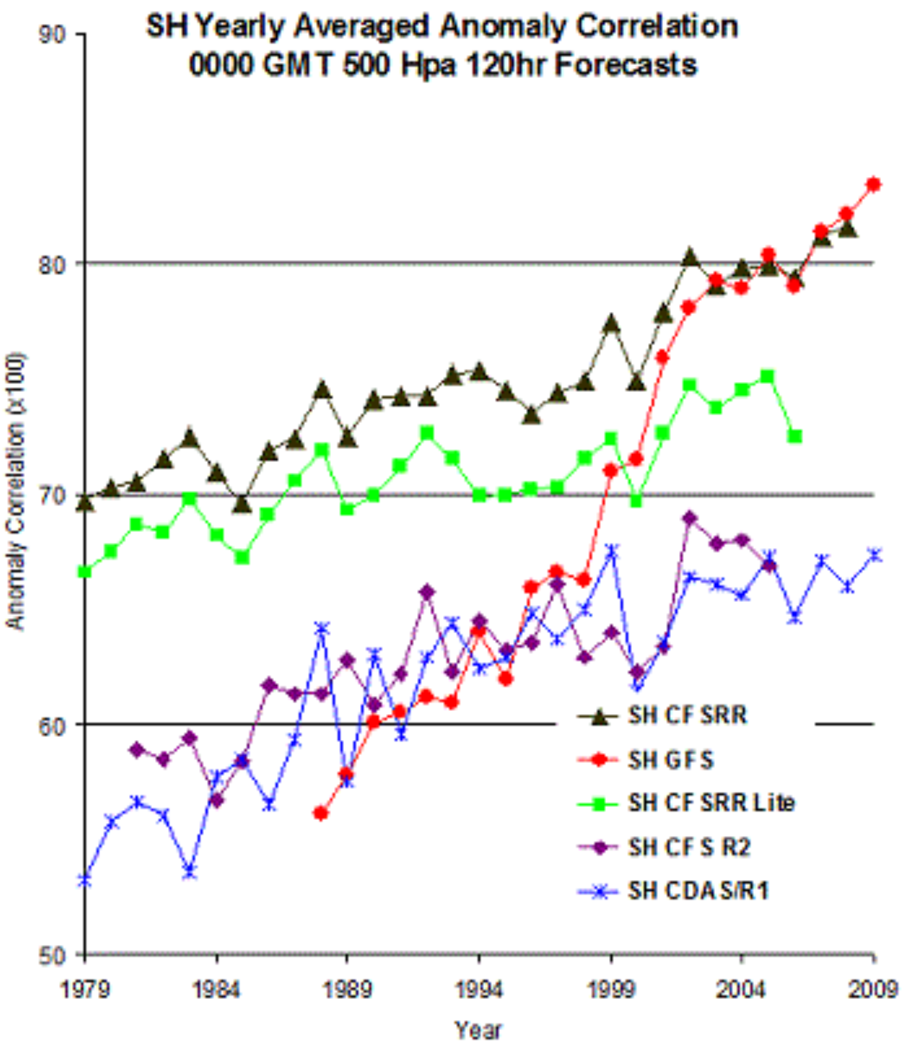
Courtesy: http://gaw.kishou.go.jp

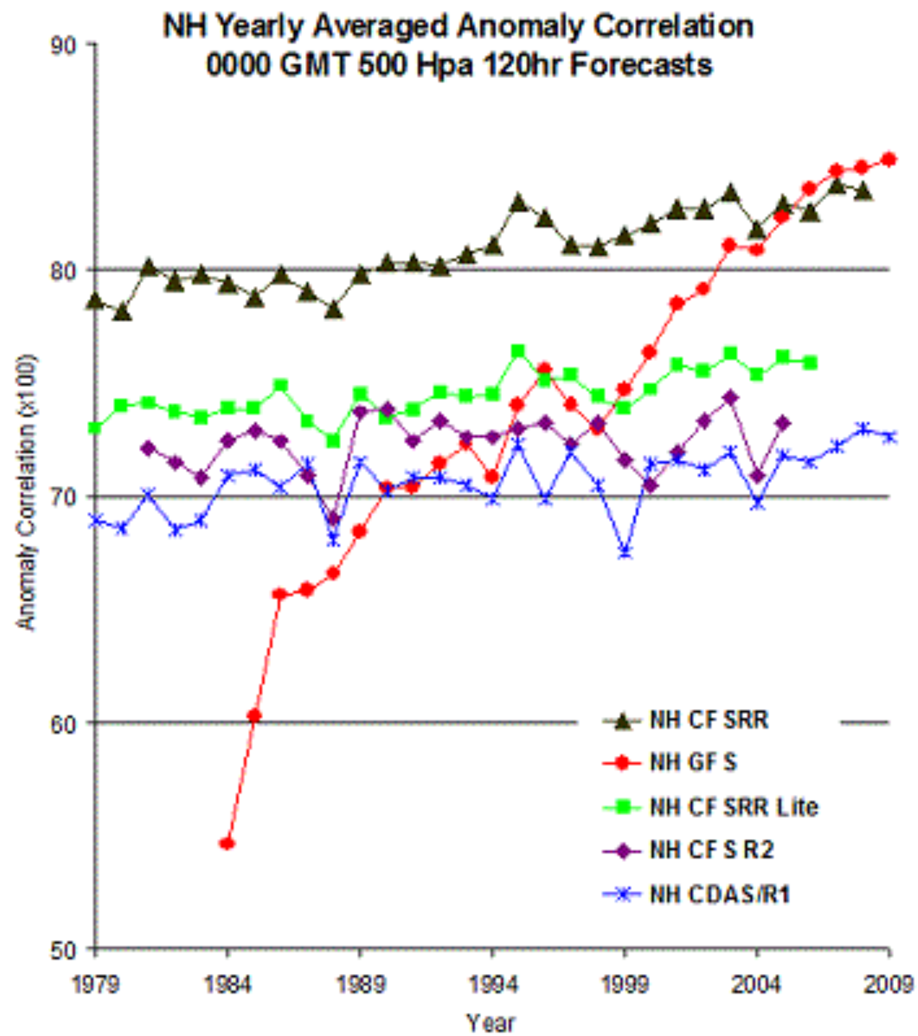


The linear trends are 0.66, 1.02 and 0.94K per 31 years for R1, CFSR and GHCN_CAMS respectively. (Keep in mind that straight lines may not be perfectly portraying climate change trends).

Huug van den Dool, CPC

5-day T126L64 forecast anomaly correlations

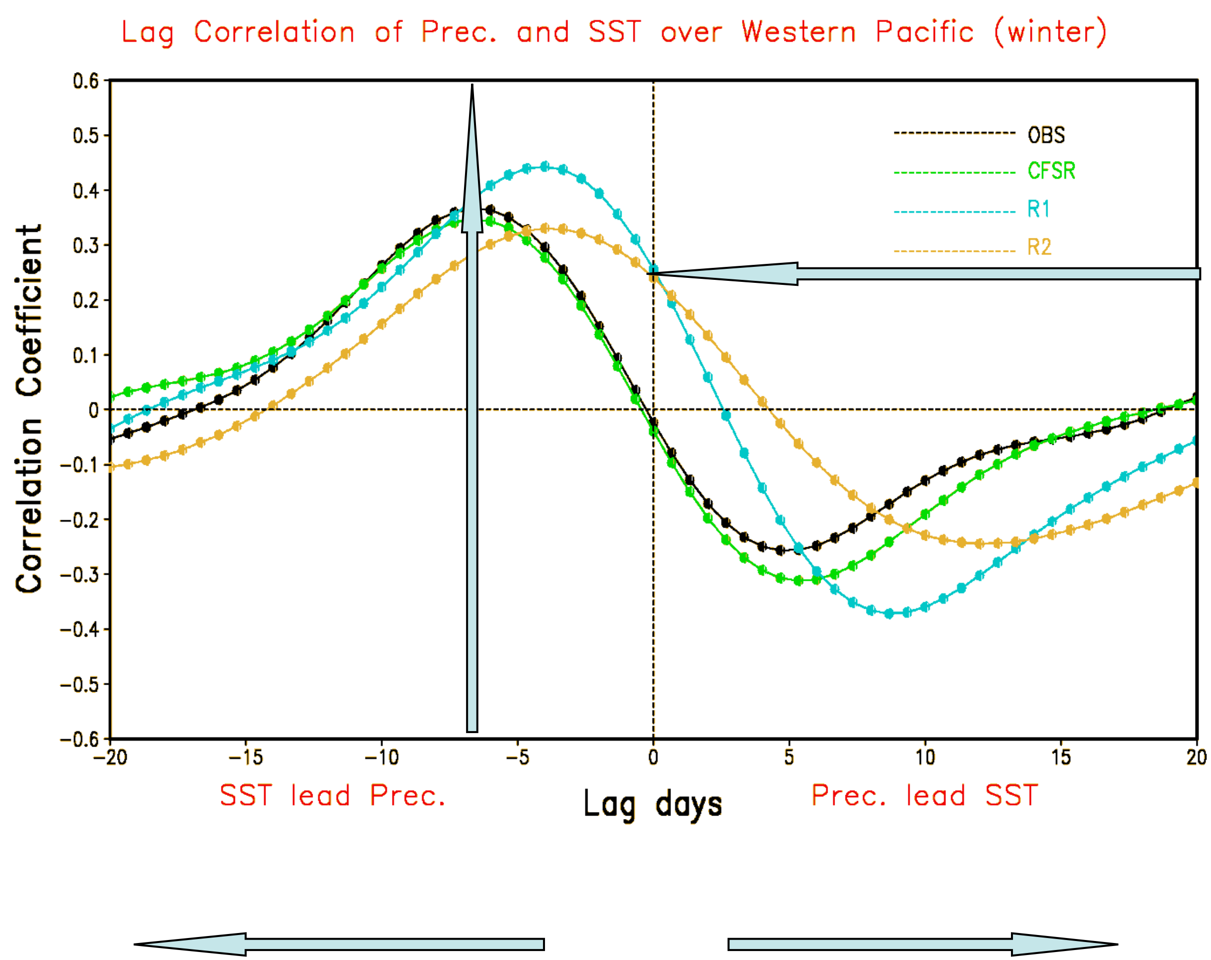




Courtesy: Bob Kistler

SST-Precipitation Relationship in CFSR

Precipitation-SST lag correlation in tropical Western Pacific



Response of Prec. To SST increase : warming too quick in R1 and R2

simultaneous positive correlation in R1 and R2

Courtesy: Jiande Wang

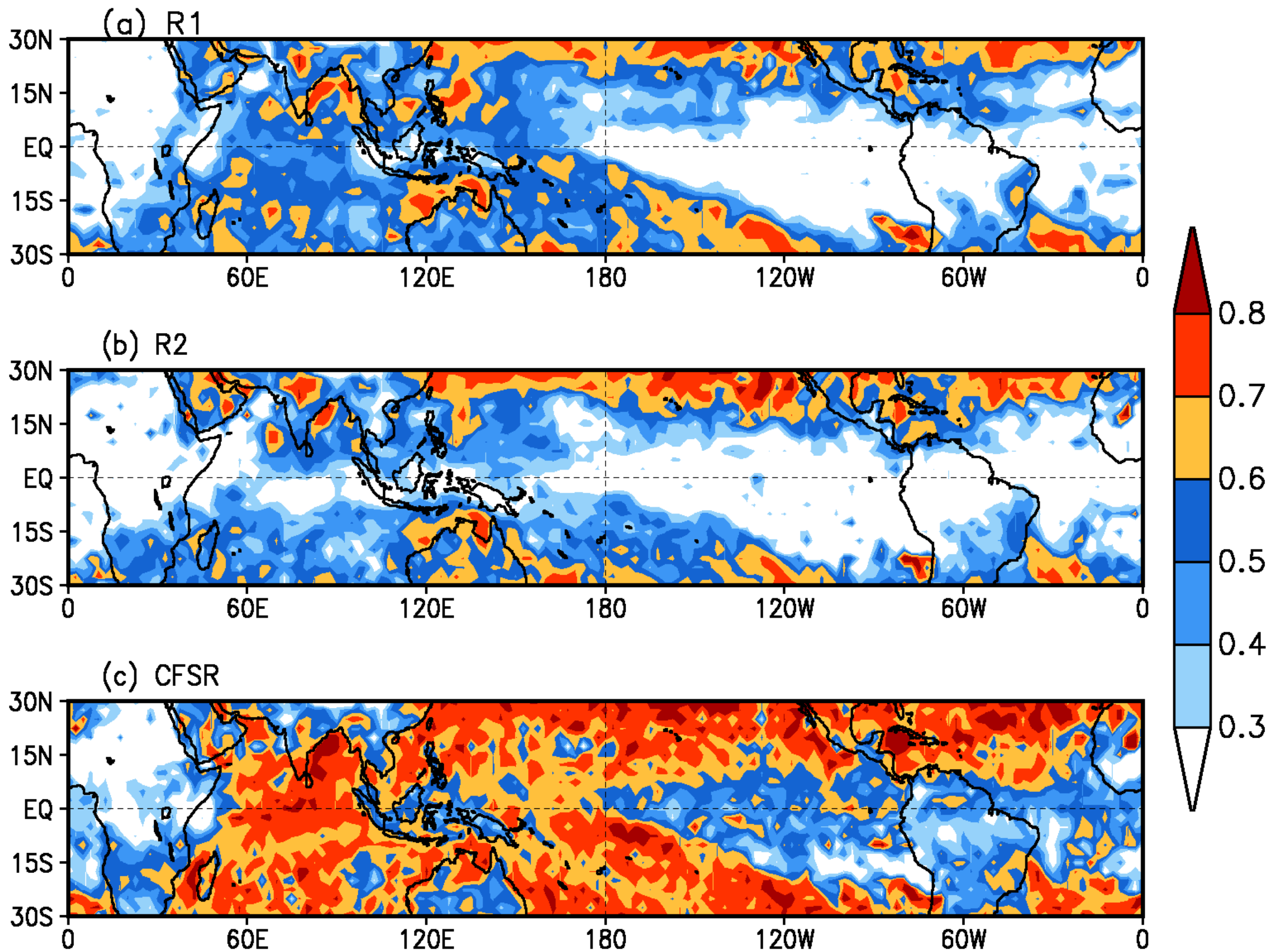
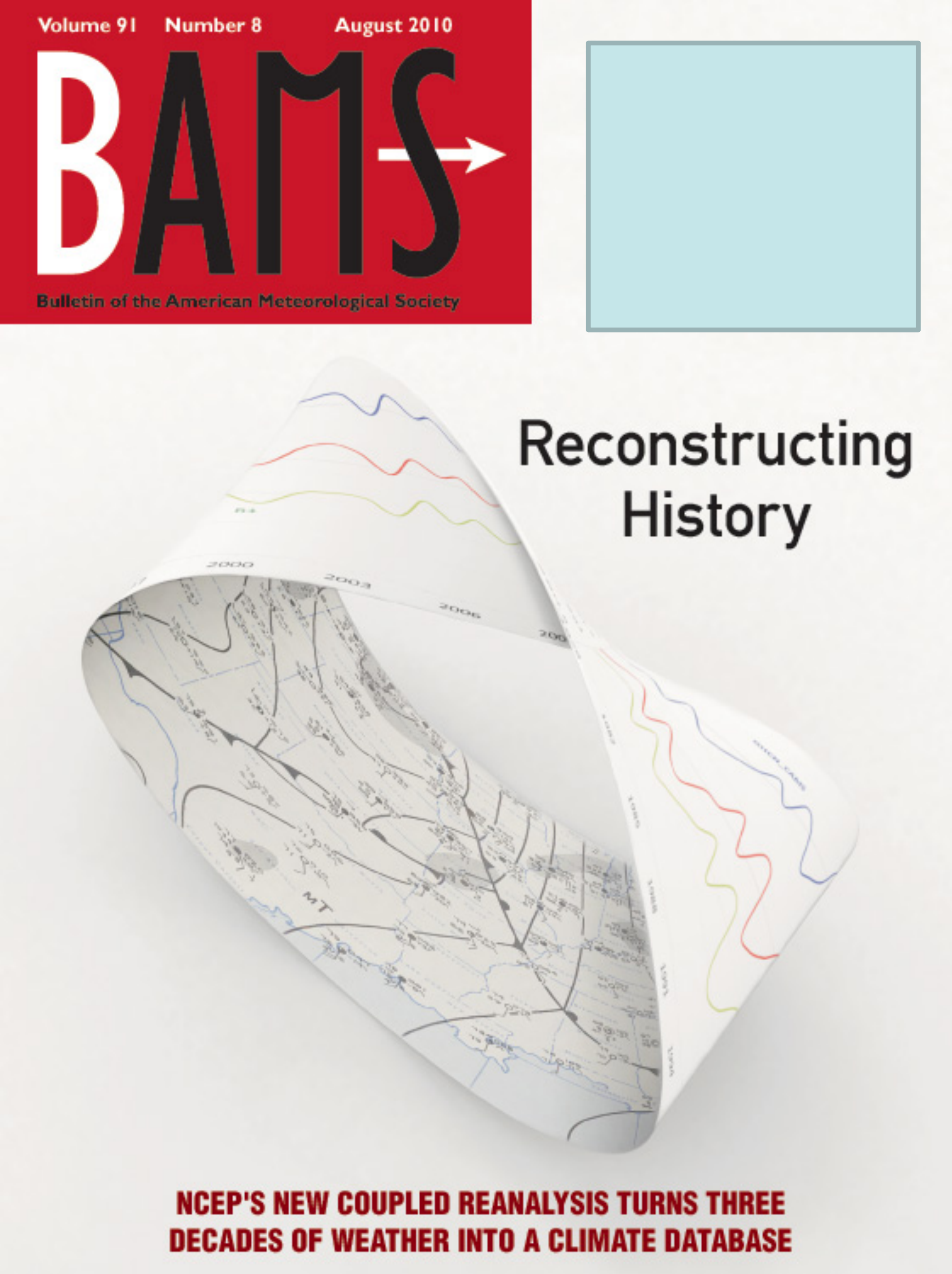


Fig. 3 Correlation of intraseasonal precipitation with CMORPH. (a) R1, (b) R2, and (c) CFSR. Contours are shaded starting at 0.3 with 0.1 interval.

Courtesy: Jiande Wang et al



The NCEP Climate Forecast System Reanalysis

Suranjana Saha, Shrinivas Moorthi, Hua-Lu Pan, Xingren Wu, Jiande Wang, Sudhir Nadiga, Patrick Tripp, Robert Kistler, John Woollen, David Behringer, Haixia Liu, Diane Stokes, Robert Grumbine, George Gayno, Jun Wang, Yu-Tai Hou, Hui-ya Chuang, Hann-Ming H. Juang, Joe Sela, Mark Iredell, Russ Treadon, Daryl Kleist, Paul Van Delst, Dennis Keyser, John Derber, Michael Ek, Jesse Meng, Helin Wei, Rongqian Yang, Stephen Lord, Huug van den Dool, Arun Kumar, Wanqiu Wang, Craig Long, Muthuvel Chelliah, Yan Xue, Boyin Huang, Jae-Kyung Schemm, Wesley Ebisuzaki, Roger Lin, Pingping Xie, Mingyue Chen, Shuntai Zhou, Wayne Higgins, Cheng-Zhi Zou, Quanhua Liu, Yong Chen, Yong Han, Lidia Cucurull, Richard W. Reynolds, Glenn Rutledge, Mitch Goldberg

Bulletin of the American Meteorological Society
Volume 91, Issue 8, pp 1015-1057.
doi: 10.1175/2010BAMS3001.1

AND NOW……..

THE SECOND ‘R’ IN

NCEP Climate Forecast System

CFSRR

Reanalysis and Reforecast

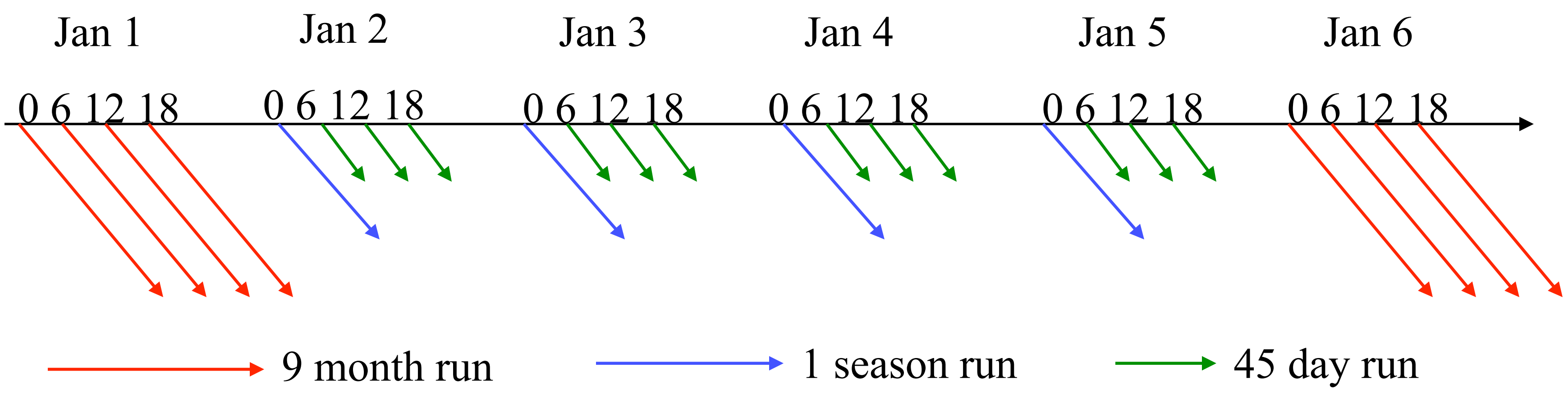
CFSV1	CFSV2
T62 horizontal resolution (~200 Km)	T126 horizontal resolution (~100 Km)
Sigma vertical coordinate with 28 levels with top pressure ~3 hPa	Sigma-pressure hybrid vertical coordinate with 64 levels with top pressure ~0.266 hPa
Simplified Arakawa-Schubert convection	Simplified Arakawa-Schubert convection with momentum mixing
Tiedtke (1983) shallow convection	Tiedtke (1983) shallow convection modified to have zero diffusion above the low level inversions
Orographic gravity wave drag based on GLAS/GFDL approach	Orographic gravity wave drag based on Kim and Arakawa(1995) approach and sub-grid scale mountain blocking following Lott and Miller (1997)

Courtesy: Shrinivas Moorthi

CFSV1 (contd)	**CFSV2 (contd)**
GFDL IR radiation with random cloud overlap and fixed CO_2 of 330 ppmv	AER RRTM IR radiation with maximum/ random cloud overlap and observed global mean CO_2
GFDL SW based on Lacis-Hansen (1974) scheme with random cloud overlap and fixed CO_2 of 330 ppmv. No aerosols or rare gases	AER RRTM SW radiation with maximum/ random overlap and observed global mean CO_2, aerosols including volcanic origin plus rare gases.
Local-*K* vertical diffusion both in PBL and free atmosphere with a uniform background diffusion coefficient	Non-local vertical diffusion in the PBL with local-K in the free atmosphere with exponentially decaying background diffusion coefficient
Second order horizontal diffusion	Eighth order horizontal diffusion
OSU 2 layer land surface model	Noah 4 layer land surface model
Coupled to near global GFDL MOM3 and climatological seaice	Coupled to fully global GFDL MOM4 and a 3 layer sea-ice model

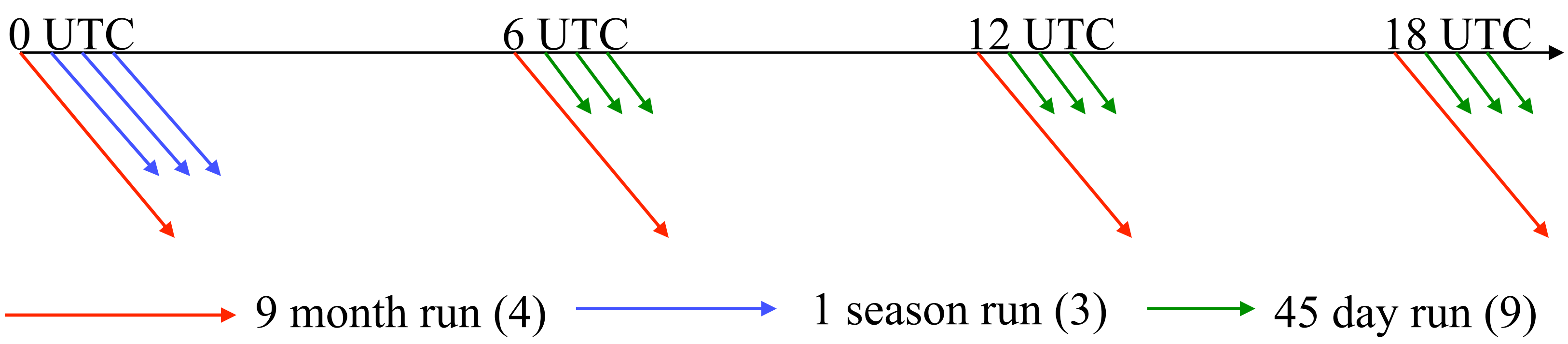
Hindcast Configuration for CFSv2

- 9-month hindcasts were initiated from every 5th day and run from all 4 cycles of that day, beginning from Jan 1 of each year, over a 29 year period from 1982-2010 This is required to calibrate the operational CPC longer-term seasonal predictions (ENSO, etc)
- There is also a single 1 season (123-day) hindcast run, initiated from every 0 UTC cycle between these five days, over the 12 year period from 1999-2010. This is required to calibrate the operational CPC first season predictions for hydrological forecasts (precip, evaporation, runoff, streamflow, etc)
- In addition, there are three 45-day (1-month) hindcast runs from every 6, 12 and 18 UTC cycles, over the 12-year period from 1999-2010. This is required for the operational CPC week3-week6 predictions of tropical circulations (MJO, PNA, etc)



Operational Configuration for CFSv2

- There will be 4 control runs per day from the 0, 6, 12 and 18 UTC cycles of the CFS real-time data assimilation system, out to 9 months.
- In addition to the control run of 9 months at the 0 UTC cycle, there will be 3 additional runs, out to one season. These 3 runs per cycle will be initialized as in current operations.
- In addition to the control run of 9 months at the 6, 12 and 18 UTC cycles, there will be 3 additional runs, out to 45 days. These 3 runs per cycle will be initialized as in current operations.
- There will be a total of 16 CFS runs every day, of which 4 runs will go out to 9 months, 3 runs will go out to 1 season and 9 runs will go out to 45 days.



RESULTS

- **MJO INDEX**
- **2-METER TEMPERATURE**
- **PRECIPITATION**
- **SST**

45-DAY HINDCASTS

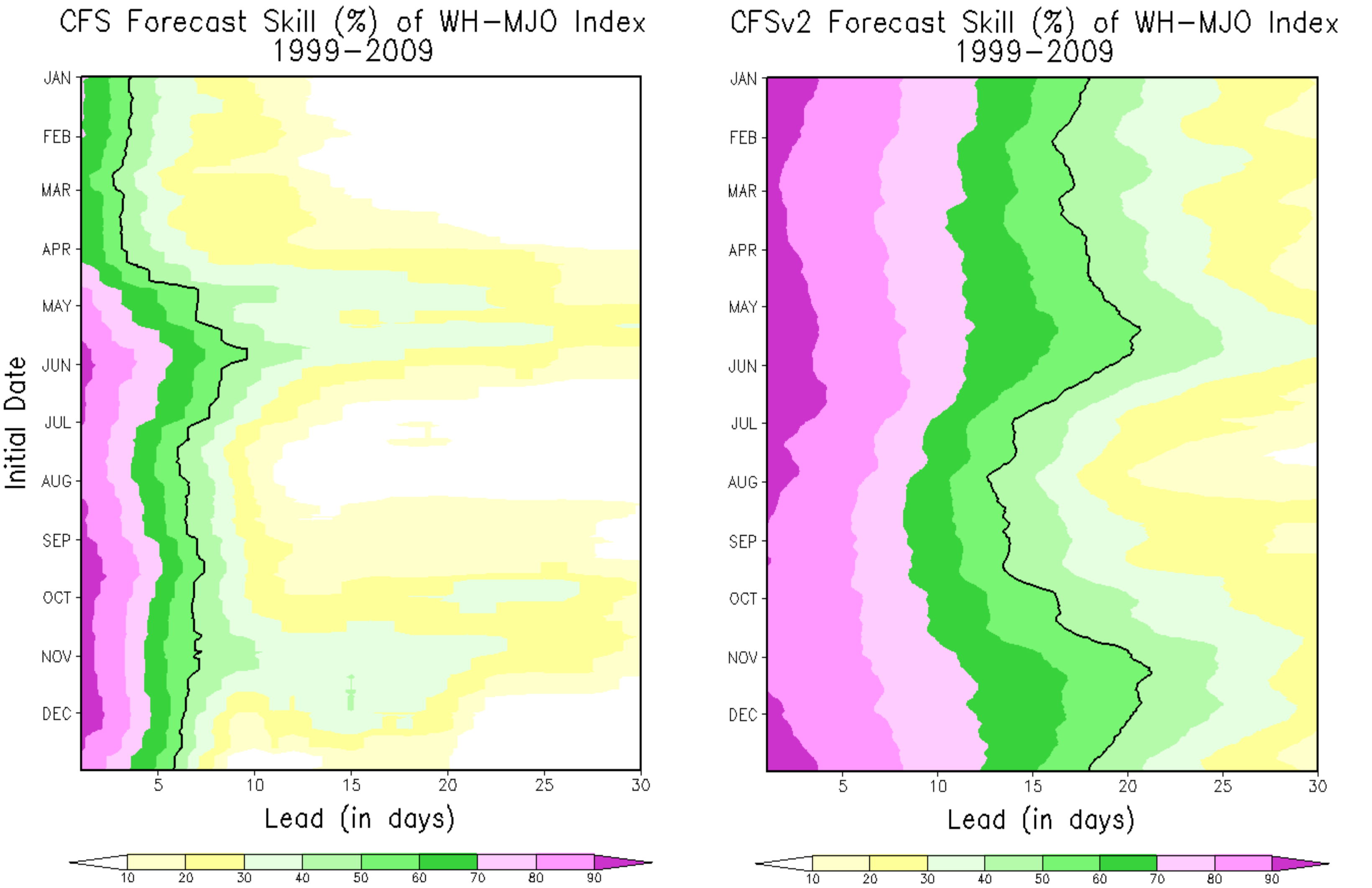
11 years: 1999-2009; all 12 months.

CFSv1 : 15 members per month, total of 180 initial states per year

CFSv2: every cycle of every day of the year, total of 1460 initial states per year.

Sample size: 1980 for CFSv1; 16060 for CFSv2.

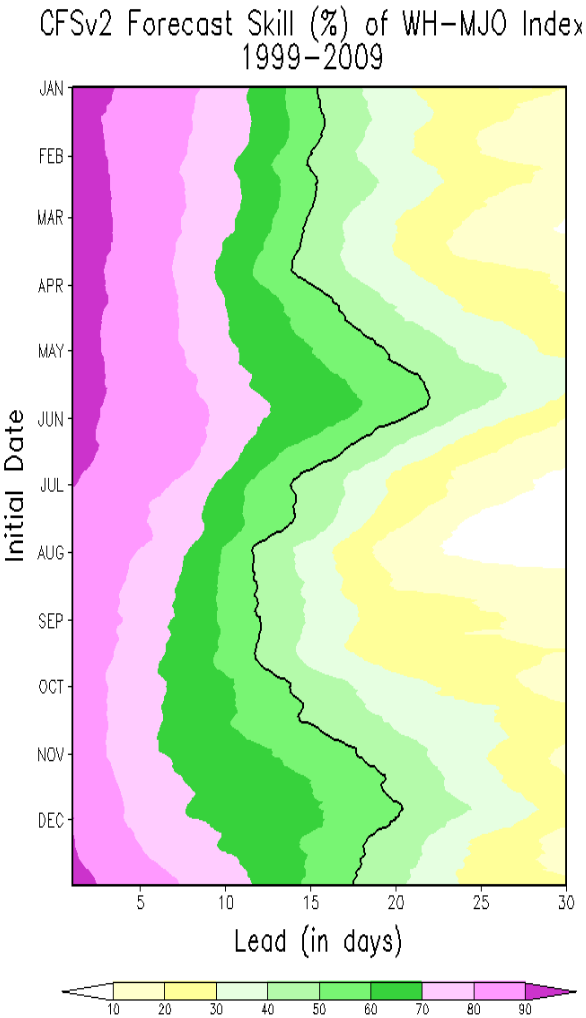
Forecast Skill of WH-MJO index



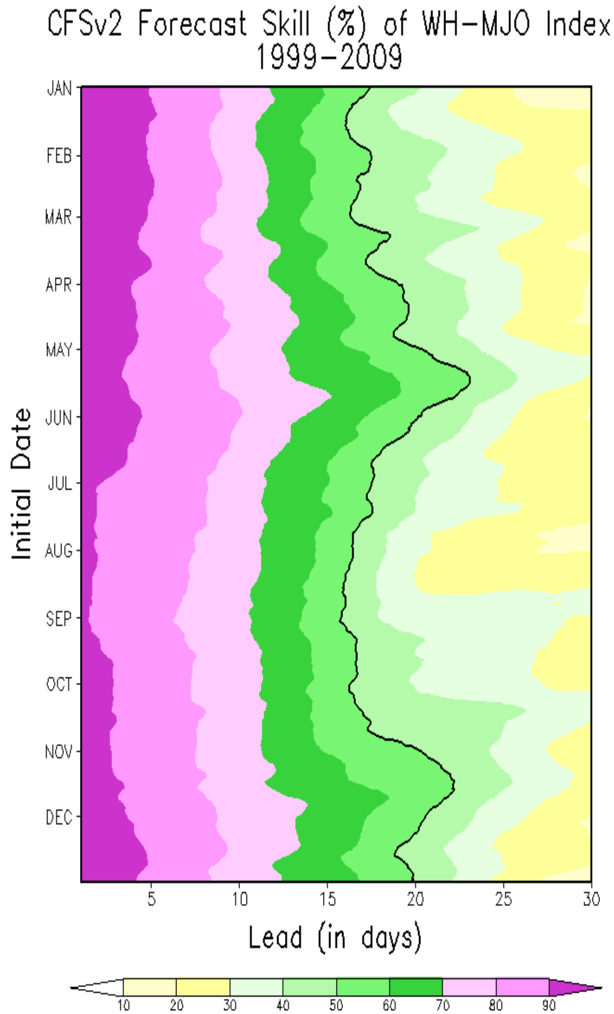
Qin Zhang and Huug van den Dool, CPC

Forecast Skill of WH-MJO index

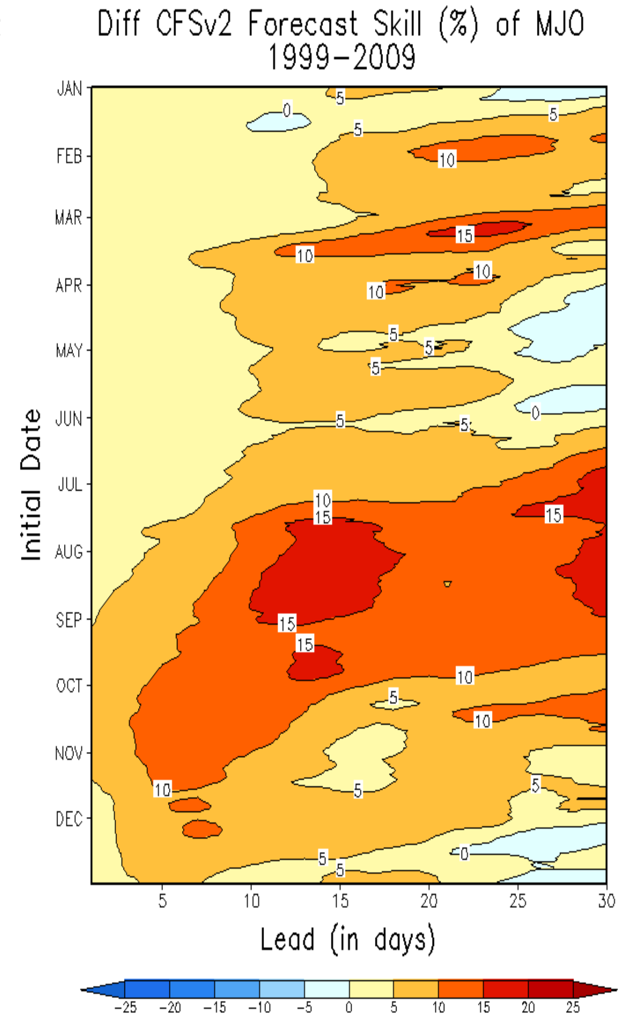
Before Model Bias Correction



After Model Bias Correction



Difference (After - Before)



Qin Zhang and Huug van den Dool, CPC

9-MONTH HINDCASTS

28 years: 1982-2009; all 12 months.

CFSv1 : 15 members per month, total of 180 initial states per year

CFSv2: 24 members per month (28 for November), total of 292 initial states per year.

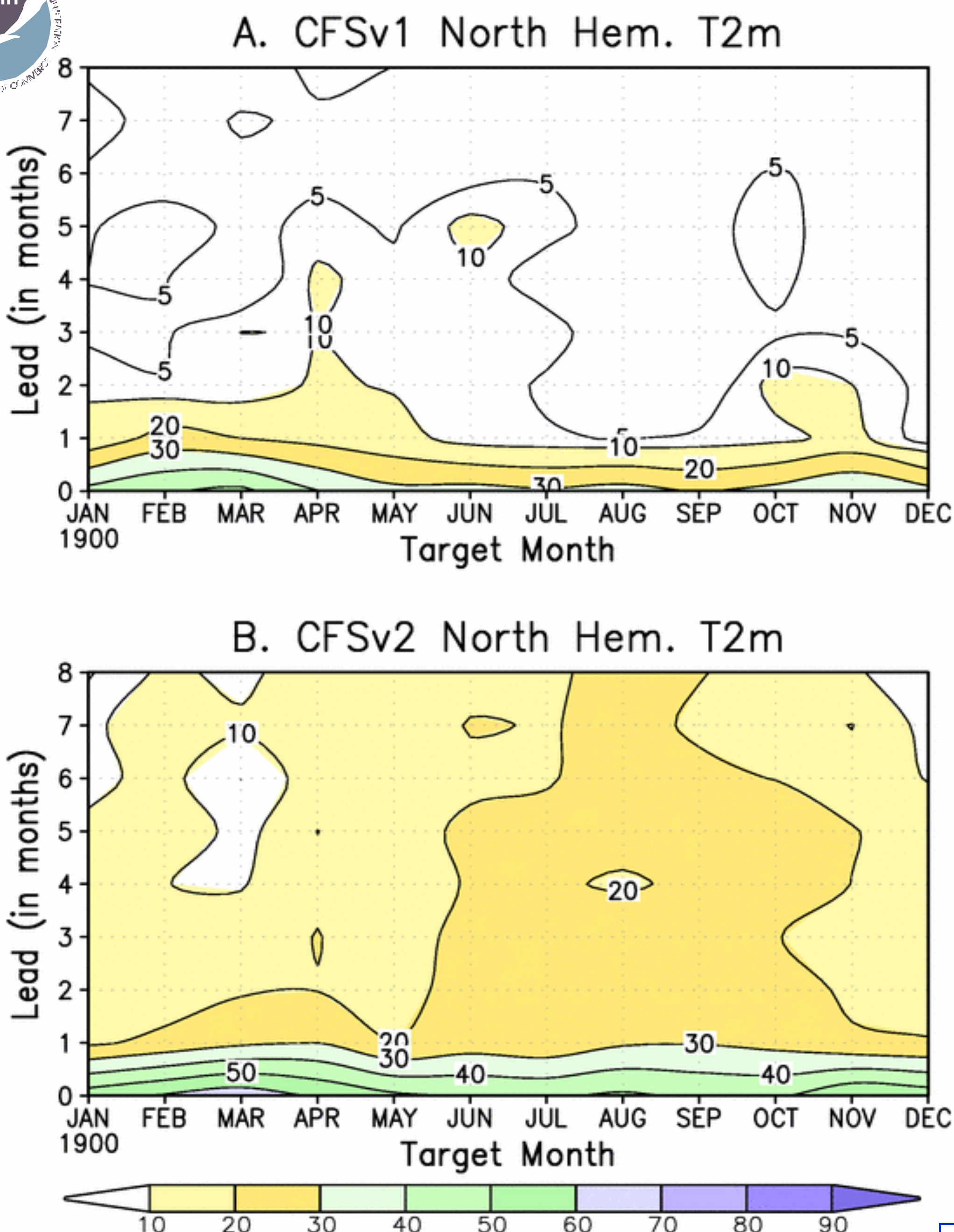
Sample size: 5040 for CFSv1; 8176 forCFSv2.

Definitions and Data

- AC of ensemble averaged monthly means
- GHCN-CAMS (validation for Tmp2m)
- CMAP (validation for Prate)
- OIv2 (validation for SST)
- 1982-2009 (28 years)
- Common 2.5 degree grid
- Variables/areas studied: US T, US P, global and Nino34 SST, global and Nino34 Prate.
- Two climos used for all variables within tropics

  30S-30N: 1982-1998 and 1999-2009

  Elsewhere: 1982-2009



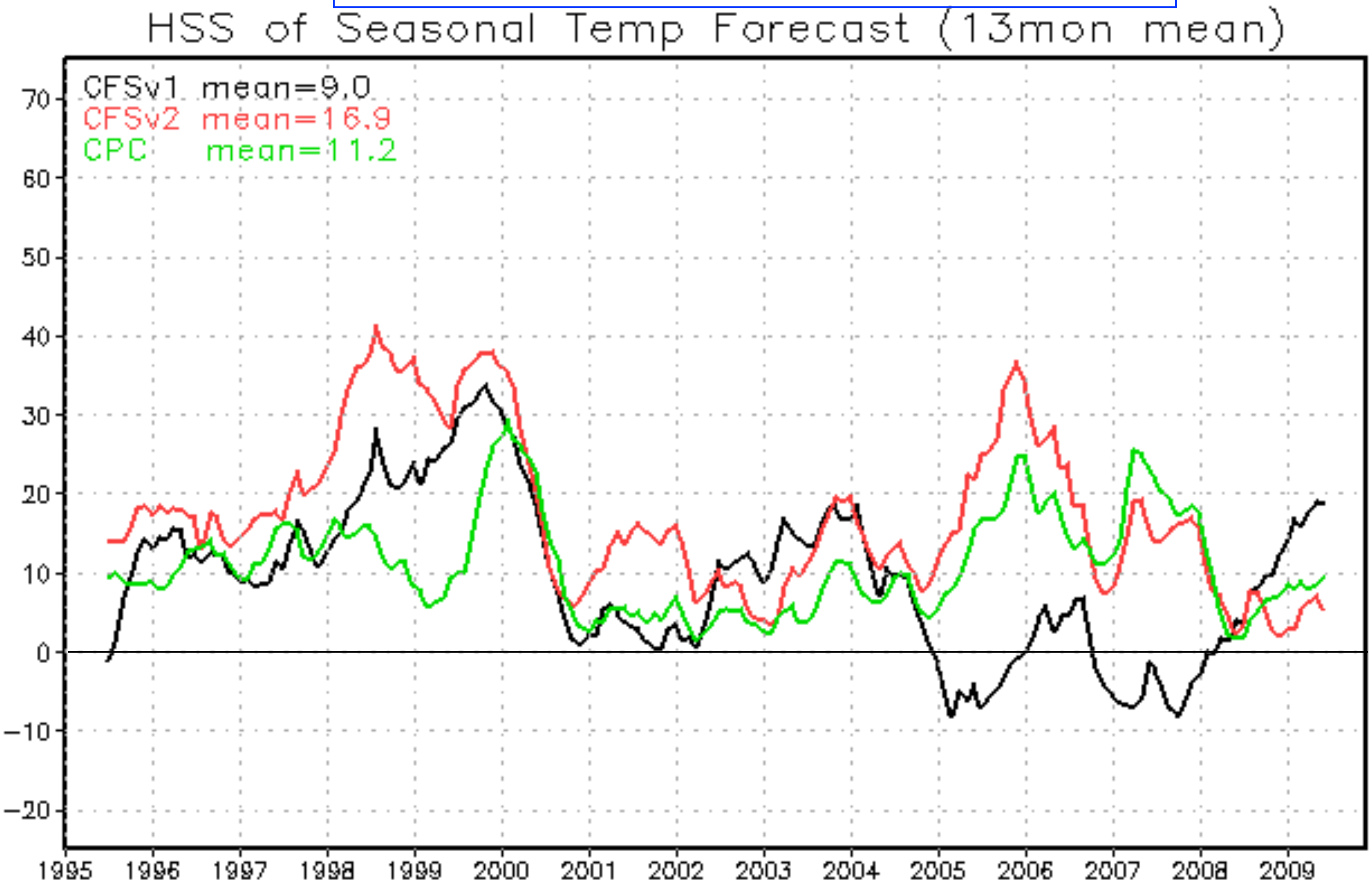
2-meter Temperature Ensemble skill of Northern Hemisphere (all land north of 20°N)

CFSv2 clearly has more skill

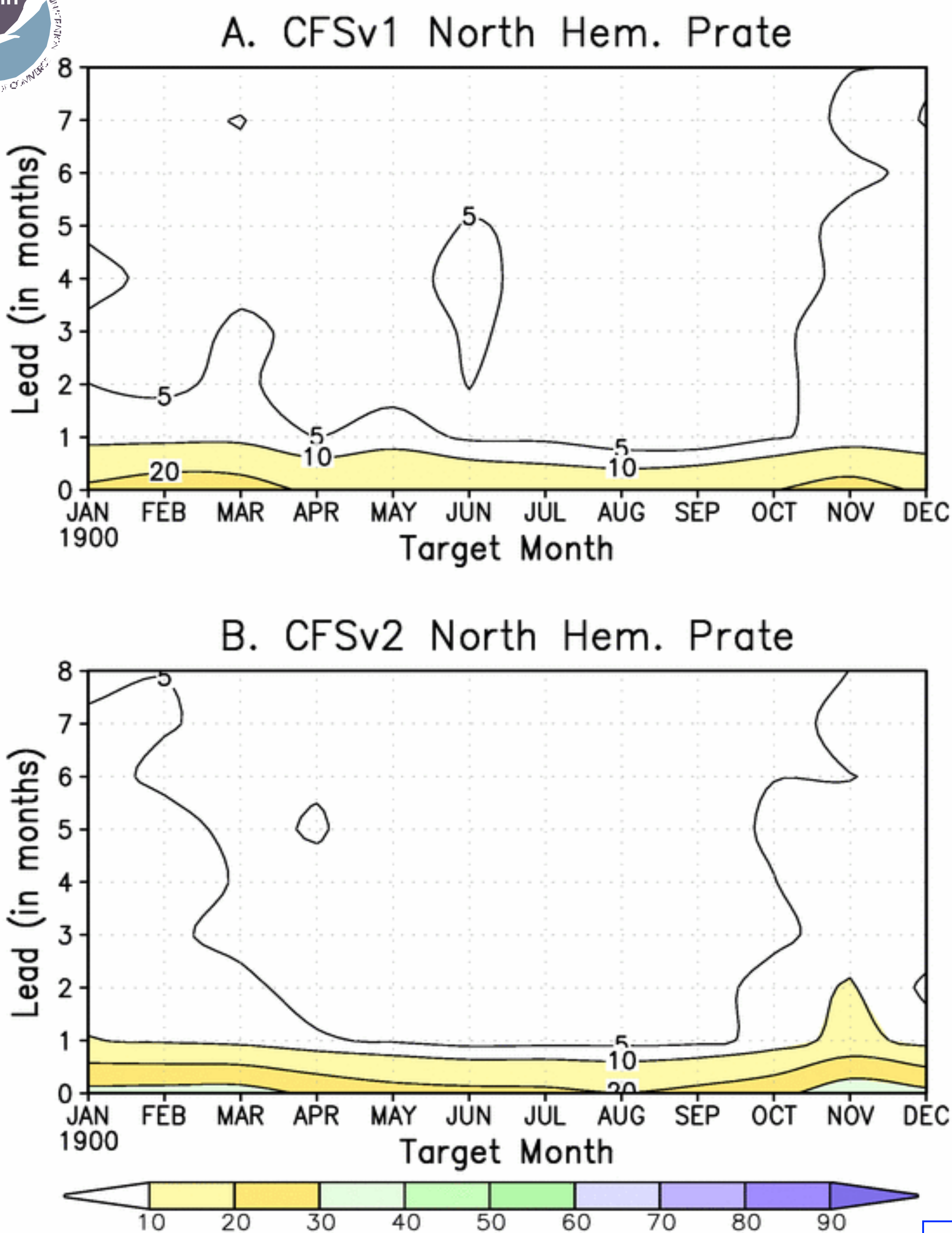
Huug van den Dool & Emily Becker, CPC

Heidke Skill Score for 2-meter Temp

More skill for CFSv2



Peitao Peng, CPC



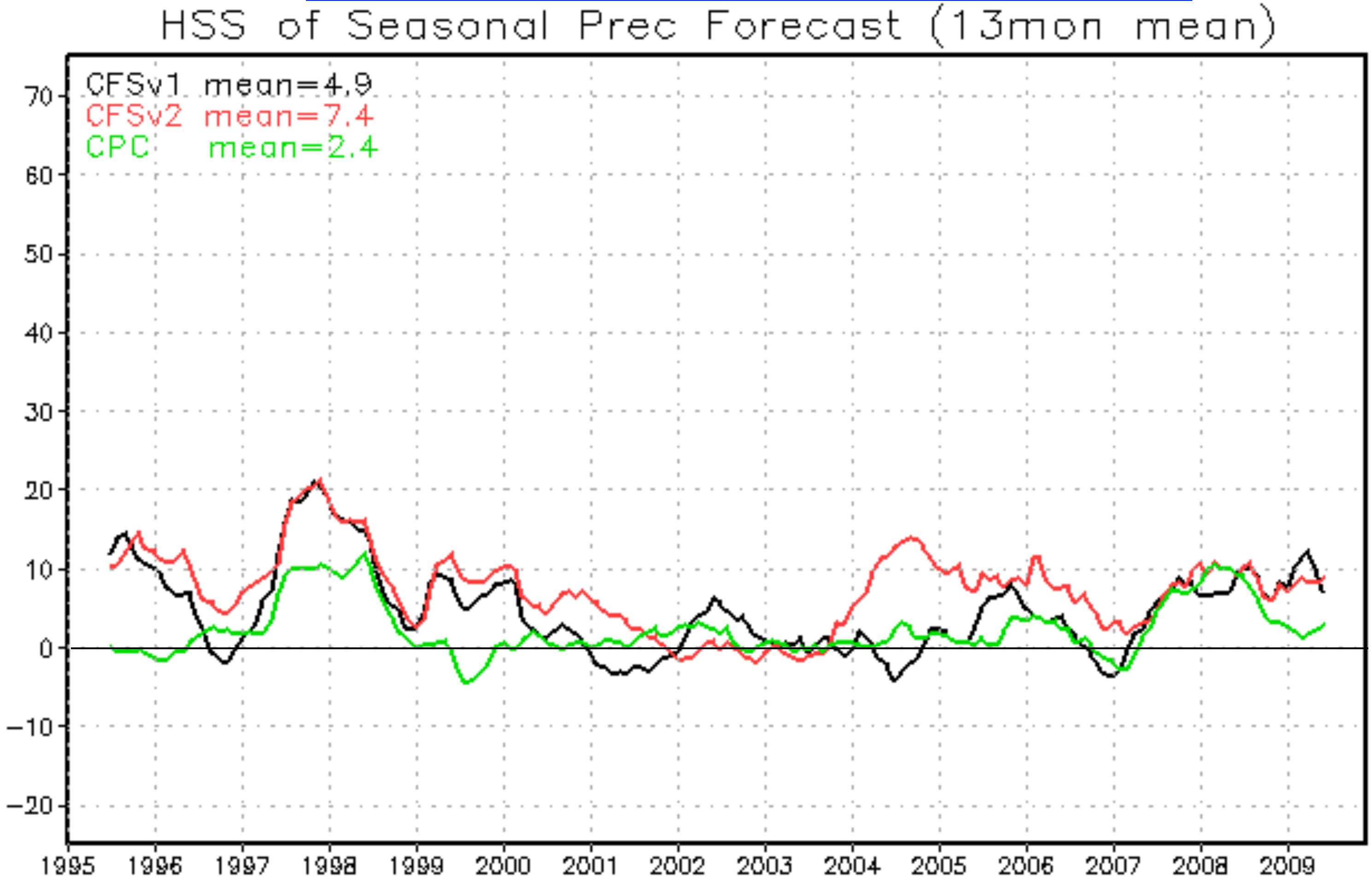
Precipitation Ensemble skill of Northern Hemisphere (all land north of 20°N)

Both systems have very little skill for precipitation

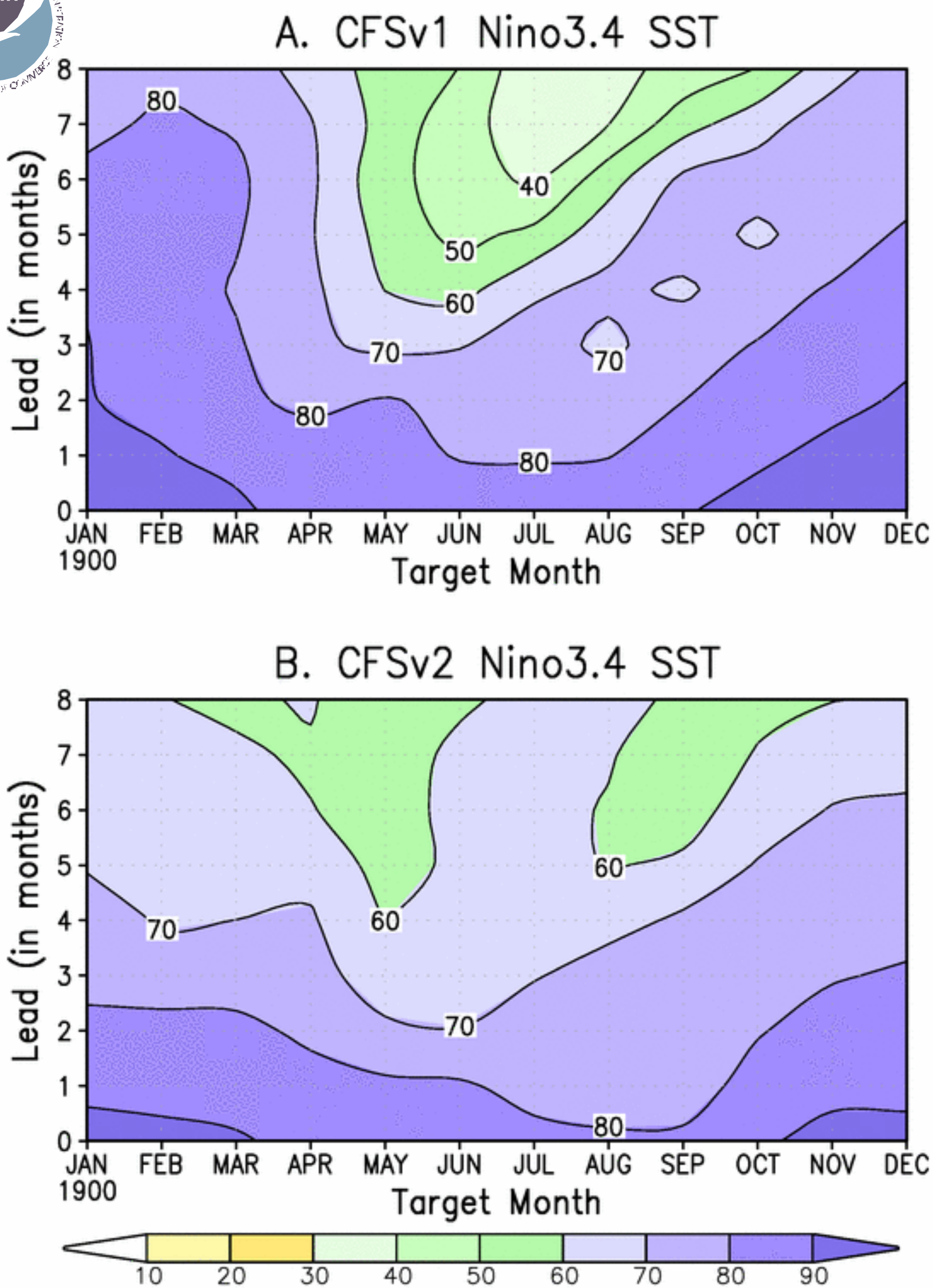
Huug van den Dool & Emily Becker, CPC

Heidke Skill Score for Precipitation

Slightly more skill for CFSv2



Peitao Peng, CPC



Sea Surface Temperature Ensemble skill of Nino 3.4

CFSv1 has a problem in that it persists large winter anomalies into the spring (a critical ENSO season) and is reluctant to go to neutral, let alone to go from La Nina to El Nino or vice versa (as is common in spring).

The standard deviation for MAM is clearly improved in CFSv2.
There appears to be much less of a "spring barrier" in CFSv2.

Huug van den Dool & Emily Becker, CPC

THE BOTTOM LINE

Anomaly Correlation: All Leads (1-8), All Months (10)

Green is good Red is not good

Model	US T	US P	Nino34 SST	Nino34 Prate	Global SST (50N-50S)
CFSv2	16.3	9.5	77.2	54.5	42.2
CFSv1	9.5	10.3	71.8	52.8	37.7
CFSv1v2 CFSv1v2-CFSv2 %tage change	15.4 -0.9 (-5.8%)	12.2 +2.7 (+22%)	78.3 +1.1 (+1.4%)	57.0 +2.5 (+4.4%)	45.4 +3.2 (+7%)

Anomaly Correlation for other Regions (collaboration with EUROSIP and India)

All Leads (1-8), All Months (10)

Green is good Red is not good

Model	US T	Europe T	India T	US P	Europe P	India P
CFSv2	16.3	16.4	48.1	9.5	6.0	18.9
CFSv1	9.5	9.6	2.4	10.3	4.5	18.0
CFSv1v2 CFSv1v2-CFSv2 %tage change	15.4 -0.9 (-5.8%)	15.5 -0.9 (-5.8%)	30.7 -18.1 (-59%)	12.2 +2.7 (+22%)	6.2 +0.2 (+3.2%)	22.8 (+3.9) (+17.1%)

MILESTONES

Aug 2004:	**CFSv1 was implemented into operations.**
Aug 2004 - Dec 2006:	**Test version of the CFSv2 ready. Upgrades to virtually every part of the data assimilation and forecast model developed over 2 ½ years.**
Jan 2007 - Dec 2007:	**Pilot studies and testing of the full data assimilation and forecast system at low resolution (1 year)**
Nov 2007:	**CFSRR Science Advisory Board Meeting**
Jan 2008 – Dec 2009:	**CFS Reanalysis complete for 31 years 1979-2009 (2 years)**
Jan 2010 – Dec 2010:	**CFS Reforecasts complete for 28 years 1982-2009 (1 year)**
Dec 2010 – Mar 2011:	**NCO parallel implementation of CFSv2 (4 months)**
March 30, 2011:	**Operational implementation of CFSv2**

COMPUTER RESOURCES

Very large and complex projects such as the CFSRR are 24/7 operations. We had to utilize 1 or 2 mainframe computers at near 100 % utilization to finish the project in time.

This entire CFSRR project was carried out on 6 different IBM mainframe computers (Zephyr, Haze, Mist, Dew, Cirrus and Stratus).

It involved running the CFSv2 for over 10,000 years of Reforecasts and 32+6 years (overlap) of Reanalysis.

HUMAN RESOURCES

When we scoped out the human resources for the project at the start, we asked for 8 people, six of whom would be on call 24/7 and we would rotate them thru, so there would be a down time for everyone.

We were given 4 FTEs. These four people were 24/7 for nearly 4 years !! Their dedication, discipline and team work made it possible for the CFSv2 to be implemented in March 2011. They are: Xingren Wu, Jiande Wang, Sudhir Nadiga and Patrick Tripp.

In addition to this core team, there were a few scientists in EMC that were on call 24/7 to help with keeping the system running smoothly. They are: Hua-Lu Pan, Shrinivas Moorthi, Dave Behringer, Mike Ek, Bob Kistler, Jack Woollen, etc.

Many scientists from both EMC and CPC were also involved in the design, execution and monitoring of the system.

Technical help from the NCEP Central Operations is also acknowledged.

DATA ARCHIVAL

The CFSRR project has generated more than 3 Petabytes of data on our mass store system.

NCDC is the main source of all CFSRR data distribution. NCAR does distribute some of the CFSR (Reanalysis) data.

Nearly ½ TB of data is now generated in operations everyday. These are distributed via the TOC in real time.

Discussions on the archival of the real time operational CFSv2 products at NCDC are underway.

CFS VERSION 3

- *Introduction of a global hybrid ensemble-variational data assimilation system*

  NCEP will implement its global hybrid data assimilation system in Spring 2012. This system uses an Ensemble Kalman Filter (EnKF) to generate flow-dependent covariances used in the variational analysis. A four-dimensional capability, either with a more traditional 4-D variational approach or through a 4-D EnKF is also likely before 2015.

- *Improve analysis coupling*

  The operational CFSR uses a coupled atmosphere-ocean-land-sea ice forecast for the analysis background but the analysis is done separately for each of the domains. In the next reanalysis, the goal is to increase the coupling so that, e.g., the ocean analysis influences the atmospheric analysis (and vice versa). This will be achieved mainly by using a coupled ensemble system to provide the background and the EnKF to generate structure functions that extend across the sea-atmosphere interface. The same can be done for the atmosphere and land, because assimilation of land data will be improved for soil temperature and soil moisture content.

CFS VERSION 3

- *Increase the specification of analysis uncertainty*

  The EnKF also provides error bars on the accuracy of the Reanalysis, something entirely missing in the present CFSR.

- *Increase the analysis variables to provide more climate-relevant quantities*

  The next CFSR will provide aerosol and chemical constituents such as dust, black carbon, sulfates, carbon dioxide, methane, nox, and other green house gases. In the ocean, some biogeochemical constituents will be possible with remote sensing of "ocean color."

CFS VERSION 3

- *Increased resolution system*

The resolution can be increased in proportion to increased computing power.

This will result in better assimilation of isolated data observed in the vicinity of steep topography.

It will also allow a better description of extremes over the period 1979-2015, along with changes in climate that can be guided by forcing functions (aerosols, GHGs), and observations amenable to assimilation. One example of an improved description of assimilating extremes would be hurricanes and storm surge events that become better resolved at high resolution. Another example is better hydrology to improve the realism of extremes in droughts, floods and river flow.

Higher resolution and better topography, along with improved physics of the boundary layer and improvements to both shallow and deep convection, will help the analysis at the interfaces, ie. sea surface temperature, 2-meter air temperature and precipitation. Producing a better daily cycle in each of these three interface variables is absolutely necessary.

CFS VERSION 3

- *Increased resolution system* (contd)

  Increased resolution of the coupled system will also improve the representation of shallow coastal oceans and ecosystems.

  Increased resolution into the stratosphere and higher comes at an opportune time, now that nature offers us an experiment with a quiet sun from 2008 onward. This should yield insight into the chemistry of such vital elements as ozone, and give a better description of both the trend and interannual variation of the ozone hole from 1979-present.

  An increase in resolution and the embedding of regional models into the global domain will also help in make more realistic downscaling studies possible.

CFS VERSION 3

- *Mitigate some of the problems in the operational CFSR*

  Among the toughest problems is the analysis of sea-ice. The period 1979-2015 offers hitherto hard to explain, variations in the extent and thickness of the sea-ice in both polar regions. The modeling of sea ice, shelf ice, sheet ice and glacial ice needs to improve.

  Special attention has to be given to the coupling of seaice to fresh water from atmosphere and continental runoff, and its interaction with meridional overturning currents in all ocean basins (especially the North Atlantic) and marginal seas (Mediterranean, Baltic etc).

CFS VERSION 3

NEMS:

The NOAA Environmental Modeling System will be the vehicle used to make seasonal forecasts. The NEMS superstructure allows the coupling of multiple-model geophysical components for both weather and climate prediction.

Multi-model Ensemble:

The ensemble coupling strategy in NEMS is wrapped around the full Earth system components. That is, each member is a fully coupled geophysical component. The NEMS ensemble coupler supports stochastic state forcing among its full geophysical components, allowing controlled ensemble spread with consistent physical members.

CFS VERSION 3

Regional climate

A major advantage of a unified modeling system is the capability of supporting regional weather and climate models within the global system. The regional climate models will effectively downscale the global seasonal and climate predictions. The regional capability can also be seamless from daily to seasonal forecasting.

Data assimilation

The coupled hybrid ensemble Kalman filter data assimilation system will not only support consistent ocean and atmosphere observation analysis, it will also naturally support self-consistent ensemble initial conditions for both the weather and climate prediction capability.

CFS VERSION 3

Obviously, all this work cannot be done at NCEP alone.

We look forward to strong collaborative efforts with the external community to make this happen.

THANK YOU !!